MEMORANDUM FOR: SAF/PAS
1690 Air Force Pentagon - 5D227
Washington DC 20330-1690

MAY 24 2002

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SUBJECT: Paper approval for: Spatial and Spectral Characterization of the Crosstrack Infrared Sounder (CrIS): Test Development

Enclosed are the required ten (10) copies of the subject paper. This paper will be released at the annual meeting of SPIE (International Society for Optical Engineering) in July of '02. It was written by, and will be presented by employees of ITT Industries.

The program office has reviewed the information in the attached papers and found it appropriate for public disclosure without change.

Point of contact on this matter is Capt. Christina Muth, NPOESS IPO/ADA at 301-427-2084 (Ext. 114).

Attachment: Presentation—10 copies

Spatial and Spectral Characterization of the Crosstrack Infrared Sounder (CrIS): Test Development

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ABSTRACT

In the CrIS Acceptance Test Program two of the most important sets of requirements to verify are the spatial and spectral requirements of the sensor. The development of the test program to verify these requirements starts with the understanding of the system level requirements and how they are allocated to the sensor and module levels. With the requirements knowledge and the verification method in hand the developer selects from proposed concepts the test most appropriate concept for each requirement or test. For the chosen concept the developer derives the requirements for the test and test equipment needed to verify the system requirements. The collimator serves as an example of the flowdown of system requirements for the spatial and spectral uncertainties to test requirements and test equipment requirements. Since the collimator performance is critical for the verification of requirements, the performance data on the collimator are reviewed. Models and simulations are also key tools for developing the tests. Examples of models used for the spatial and spectral requirements are an ILS model, a gas absorption model and an edge response model. This paper serves as a summary of the processes used and requirements needed to develop the spatial and spectral characterizations for the CrIS sensor.

Keywords: Test development, ILS, collimator,

1. INTRODUCTION

The CrIS is one of the new atmospheric sensors being developed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS). As the name states it is the next generation sounder for the polar orbiting satellite that will produce the atmospheric profiles of temperature, pressures and water vapor. The CrIS is the first operational interferometric sounder to provide the atmospheric profiles for weather forecasting. The focus of this paper is the development of the test program for verifying the spatial and spectral requirements of the CrIS sensor. The test development begins with the understanding of the system, sensor and module level requirements. Knowing the requirements, the developer then proposes one or more concepts for performing each of the tests from which one is selected. With the requirements and test concept in hand the developer starts to derive the requirements for the test equipment, the test procedure and the data analysis that will be needed to verify that the requirements are met. One tool that the developer may use to aid in the development of derived requirements is a model or simulation of the test. This paper walks the reader through parts of each of these processes. Before beginning the test development, it is useful to provide a brief overview of the CrIS sensor.

1.1 CrIS Overview

The CrIS sensor is a spectral radiometer that will provide accurate measurements of the infrared radiance from the earth's atmosphere for purposes of determining the temperature, moisture and pressure profiles of the earth's atmosphere. The CrIS sensor provides spectral coverage from 650 cm^{-1} to 2550 cm^{-1} (3.9 to 15.4 micrometers) creating 1305 spectral channels of radiance in three bands: long wave infrared (LWIR), mid wave infrared (MWIR) and short wave infrared (SWIR). CrIS uses a Michelson interferometer with a maximum optical path difference of 0.8 cm to accomplish the wavelength separation. The CrIS sensor has three separate focal planes each with a 3 by 3 array of discrete field stops, focusing optics and detectors. The field of regard for the CrIS sensor is stepped to each of 30 crosstrack locations such that the ground coverage is at least a 2200 km swath (+/- 48.33 degrees) on earth.

The CrIS sensor consists of nine modules as shown in Figure 1. The Scene Selection Module (SSM) controls the LOS pointing for the sensor. The Internal Calibration Target (ICT) provides a stable and accurate blackbody source for radiometric calibration. The Fourier Transform Spectrometer (FTS) or Michelson Interferometer provides for the wavelength separation. The Telescope provides the energy collection and focuses the energy onto the detectors. The Aft Optics separates the radiance into three spectral bands. The Detector Preamp provides the detectors that convert the infrared radiance to an electrical signal and the preamplifiers for the signal chain. The Cooler Module provides for the temperature control of the focal planes. The Structure provides the stable support for all the modules. The Processing and Control Electronics contains all the necessary electronics for the sensor to function. The CrIS sensor is described in more detail in References 1-6.

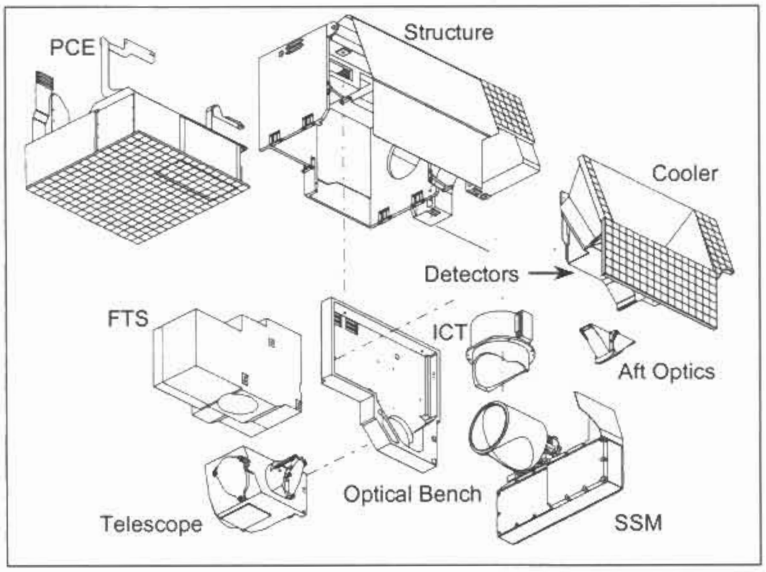

Figure 1 The CrIS Sensor Modules

2. REQUIREMENTS

The test development effort begins with a review of the system and sensor level requirements. It is natural to begin to group the requirements in to the categories of similar requirements. Spatial and spectral requirements are two of the categories that are among the most important requirements for the CrIS sensor. Radiometric requirements are the most important but will not be discussed at this time. The EDR performance depends very strongly on the knowledge of the spatial and spectral parameters of the CrIS sensor. It is the goal of the test development program to provide the means to verify the key requirements in both these categories.

2.1 Spectral Requirements

The important spectral requirements are those relating to the bands of spectral response, absolute spectral uncertainty, ILS shape uncertainty and spectral resolution. As mentioned in the overview, the CrIS sensor has three spectral bands whose required spectral ranges for the channel center wavenumbers are given in Table I.

Table I Spectral Requirements

Requirement/Spectral Band	LWIR	MWIR	SWIR
Channel Center Wavenumber Range (cm^{-1})	650 - 1095	1210 - 1750	2155 – 2550
Unapodized Spectral Resolution, nominal L	≤0.625, 0.8 cm	≤1.25, 0.4 cm	≤2.5, 0.2 cm
Absolute Spectral Uncertainty	<10(5) PPM	<10(5) PPM	<10(5) PPM
Characterize Self-apodized ILS for each spectral bin	Yes	Yes	Yes
ILS Shape Uncertainty	<1.5% FWHM	<1.5% FWHM	<1.5% FWHM
ILS Shape Stability over 30 days	<1% FWHM	<1% FWHM	<1% FWHM

The requirement for the absolute spectral calibration uncertainty over the life of the sensor is less than 10 PPM for the first flight unit and 5 PPM for subsequent flight units. In the LWIR spectral band a 10 PPM spectral calibration uncertainty corresponds to 0.0065 cm^{-1} at 650 cm^{-1}. The unapodized spectral resolution requirement is equal to 1/(2L), where L is the maximum optical path difference from Zero Path Difference (ZPD) to Maximum optical Path Difference (MPD). The on-axis unapodized spectral resolution for each spectral band shall be less than or equal to the values given in the Table I. Since L determines the unapodized spectral resolution, the nominal value for L is also given in the table.

The ILS shape uncertainty, after SDR algorithm corrections, shall be less than 1.5% of the FWHM of the ideal on-axis ILS over the operational life of the sensor. The SDR algorithm performs corrections for the effects of FOV size and FOV off axis location on the ILS. However, there is also a requirement to characterize the self-apodized ILS for each spectral bin of each FOV during ground testing. In addition to gaining understanding of the sensor, the self-apodized ILS data corroborates the model that will be used to correct for the self-apodizing effects. In addition to the uncertainty in ILS FWHM over life, there is a requirement on the ILS stability over 30 days. The requirement states that the ILS shape stability, after SDR algorithm corrections, shall be less than 1% of the FWHM of the ideal on-axis ILS over intervals not exceeding 30 days. The 30-day interval will include environmental effects that might cause the ILS to change.

2.2 Spatial Requirements

The spatial requirements are those that define the physical dimensions over which the sensor has a response. The CrIS sensor has nine fields of view for each of the three spectral bands. Figure 2 shows the nominal sizes and spacing for the nine fields of view in each band. Each FOV has its own detector. The energy centroid of the FOV angular response defines the location of the FOV and the FWHM of the angular response in each axis determines the FOV nominal size. The FOV angular response requirements are those given in Table II, which lists the FOV shape requirements as the full width at the specified response points. Also Table II shows the allowed variation in FOV shape between channels at the specified response points. There is also a requirement that the uncertainty in the location of each FOV centroid, relative to the optical boresight, shall be known to less than 1.5% of the FOV.

Table II FOV Shape Requirements

	FOV Shape (deg, Cross Track)	FOV Shape (deg, In Track)	**FOV Matching, Channel-to-Channel, In-track and Cross-track (degrees)**
70% of Peak Response Width	> 0.874	> 0.812	+/- 0.021
50% of Peak Response Width	< 0.977	< 0.909	+/- 0.014
10% of Peak Response Width	< 1.100	< 1.024	+/- 0.021
1% of Peak Response Width	< 1.238	< 1.157	N/A

The encircled energy requirement states that the energy collected within the FWHM of a FOV from an extended source shall be greater than or equal to 95%.

Several requirements specify measurements to perform. One such measurement to perform is the Modulation Transfer Function (MTF) at 30, 20, and 15 cycles per radian. Since there are no specific requirements on MTF and since this is a sounder instrument, the purpose of the MTF measurement is a quality check to ensure that the FOV is reasonably shaped and has limited tails to its response profile. Another required measurement is a raster spot scan of each FOV with a spot not exceeding one-tenth the nominal FOV width.

Since the CrIS sensor consists of three spectral bands, it is necessary to align or co-register the three bands so that the FOVs of each band see radiance from the same region of the earth's atmosphere. The co-registration requirement states that the centroid of the FOV of all channels within a band and also for each band with the same nominal FOV location shall fall in a circle with a diameter equal to 1.4% of the geometric FOV. The goal is for spatial areas of the scenes observed by all detectors and all channels with the same nominal FOV location to overlap by at least 98.6%. In addition, chromatic aberrations in the optical system are to be included within the 1.4% value. So if there is any dispersion in the optical system, these effects are still required to be contained within the 1.4%. This requirement applies over the operational life of the sensor.

These are the key requirements for the CrIS sensor to meet in order to meet the EDR or system level requirements. These requirements have been allocated form the sensor level down to the module level. It is important for the test development engineer to review and understand the allocations of these requirements as the test design progresses.

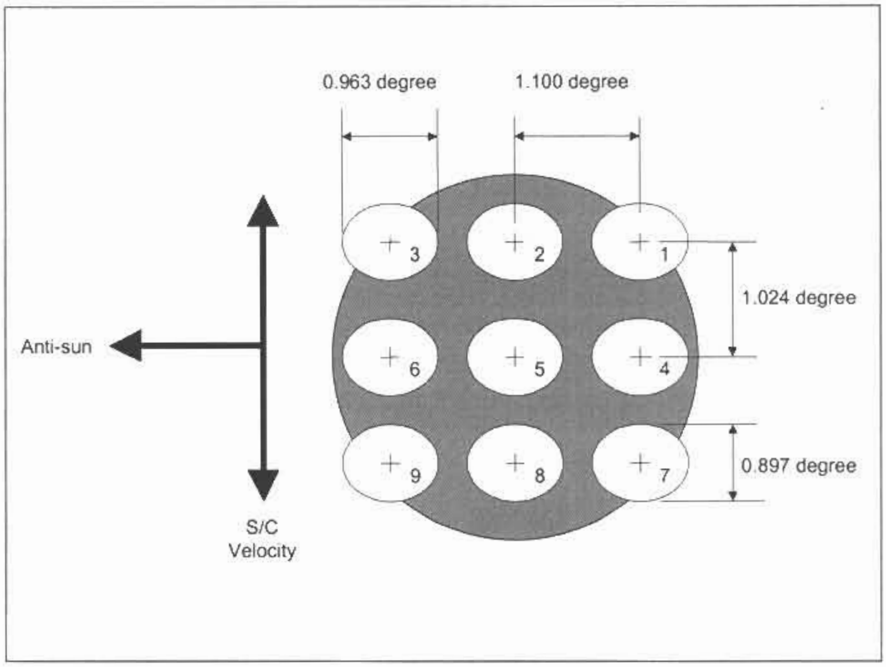

Figure 2 Nominal Field of View/Field of Regard Parameters

3. ALLOCATED AND DERIVED TEST REQUIREMENTS

The decomposition of the system level requirements leads to the allocation of requirements down to the sensor and module level. For the Spectral Uncertainty requirement the allocations, shown in figure 3, include an allocation of 2 PPM for the initial wavelength calibration uncertainty that occurs during ground calibration. The other requirements in the allocation tree are module level or sensor level allocated requirements.

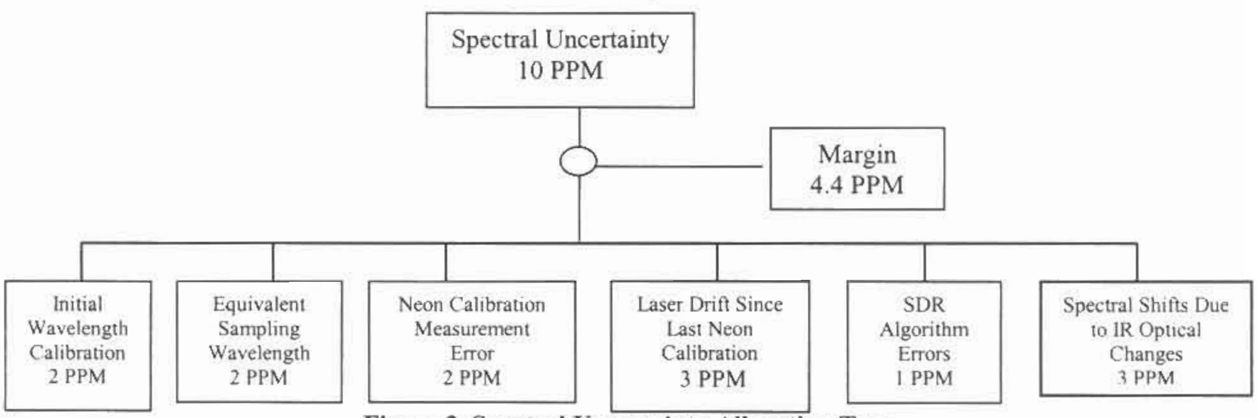

Figure 3 Spectral Uncertainty Allocation Tree

Similarly the decomposition of the requirements for the ILS Shape Uncertainty produces the allocation tree shown in figure 4. In the allocation tree the Initial Ground Calibration allocation is 0.5% of the 1.5% total. The allocation for the Initial Ground Calibration contains all the test error sources which constitutes an allocation tree of its own.

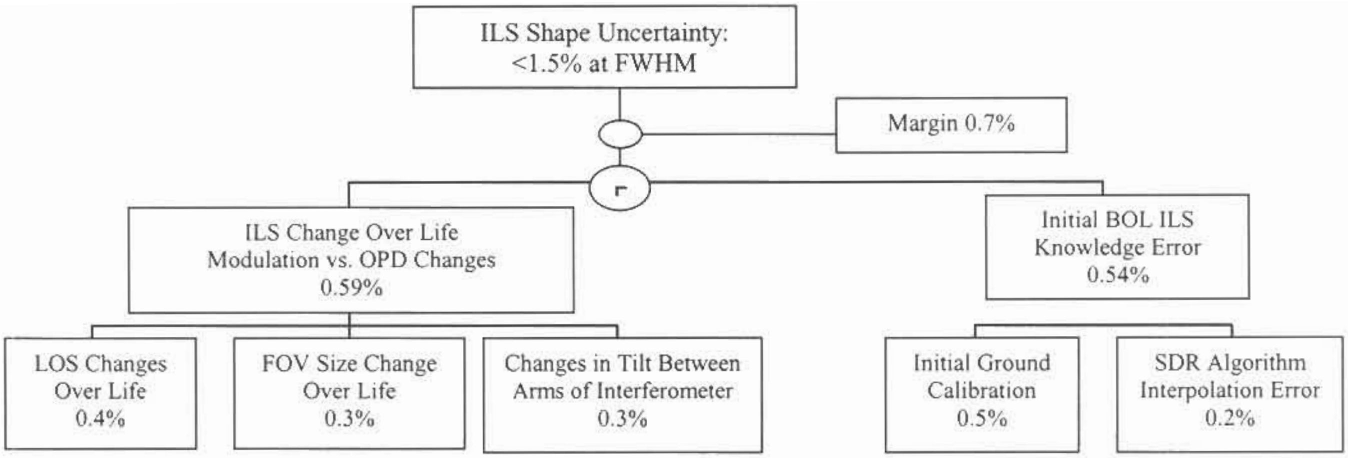

Figure 4 ILS Shape Uncertainty Allocation Tree

For the spatial requirements there are two system requirements which use allocation trees to flow requirements to the sensor and module level: the coregistration or energy matching allocation tree and the mapping uncertainty allocation tree. From the coregistration allocation tree the allocated requirement for FOV location measurement uncertainty is +/-15 micrometers at the field stop plane, which in angle space is +/-59 microradians. From the mapping uncertainty tree the allocated requirement for the knowledge of each FOV relative to the boresight is 50 microradians, where the allocated requirement for the initial FOV measurement error is 40 microradians. For the test development the 40 microradians is the root sum square of all the errors occurring during the test of which there are many.

4. TEST CONCEPTS

During the review of the allocated and derived requirements the test developer begins to develop concepts for performing the tests. Further development of the test requirements happens after a test concept is selected for each of the requirements being verified by test. With the exception of encircled energy all the spatial and spectral requirements have a verification method of test. Where possible to satisfy more than one requirement with a test, the test developer is encouraged to do so, making for a more efficient test program.

4.1 Spatial Test Concepts

The FOV shape, shape matching, size and location as well as the coregistration requirements will use the FOV angular response curves as the input for those specific calculations. So the task at hand is to develop the test concept to generate the FOV angular response curves. Typically the technique for generating these curves is to use horizontal and vertical slit scans or raster spot scans. In the case of CrIS there is already a requirement to perform a raster spot scan. Therefore, potentially the raster spot scan will satisfy all the FOV response related requirements. The generation of the FOV response curves also requires an optical system that provides a collimated beam of IR energy to the sensor that fills the entrance aperture and field of view of the sensor. Proposing slit and spot scans for the FOV measurements brings a few other facets of the test to the forefront. For instance, the SNR of the raster spot scan will not be as good as the slit scans, since the spot covers only 1/10th of the field size that the slit covers. This means that there will be 100 times more spectra to co add for the same SNR. To assess the chromatic effects on coregistration requires a broadband source with a continuous and smooth spectrum. The obvious choice for a broadband infrared source is a blackbody source. Its aperture size, temperature range, emissivity and field of view are specifications to establish.

Another concern that the developer needs to address during the concept stage is whether there are any gravity sag effects that cause differences from ground test results to the on-orbit performance. For instance coregistration errors may be impacted for certain orientations of the CrIS sensor.

The FOV requirements will be tested over temperature in the thermal vacuum chamber, so the test concepts need to be applicable for measurement both on the bench and in the vacuum chamber.

The MTF measurement at 30,20,and 15 cyc/rad requires an optical system that fills both the field and the pupil of the sensor, otherwise there will be impacts to the image quality of the system and a different MTF will result. Using discrete bar targets at the specified frequencies is one proven method for measuring the MTF. However, since there are no

specific requirements on the MTF values, the Fourier transform of the line-spread function, which is the result of a slit scan, will produce the MTF curve for all frequencies.
The verification method for the Encircled Energy requirement is Analysis_Test, where the calculation will be made using the raster spot scan data. The radial integration of the area under the response curve calculates the energy contained within a given radius.

4.2 Spectral Test Concepts

In order to measure the spectral range of the CrIS sensor and each of its spectral bands the only thing needed is a broadband source that illuminates the pupil of the sensor. This source should fill the pupil and field of the sensor but it is not required. The obvious choice for the source is a blackbody IR source. Using an undecimated interferogram and processing it outside of the normal SDR algorithm will provide a full spectrum showing the bandpass of each spectral band.

To perform the spectral calibration of the CrIS sensor requires a source with a well-known spectral signature. Preferably this will be a single line whose wavenumber has been measured by several different groups and found to agree within much less than 1 PPM. This spectral source could either be an emission source or absorption with a broadband source. The choices are either a laser with a well-known emission line or a gas with well-known absorption lines. The source needs to fill the field of view of the sensor. At least one line is needed per spectral band, thus requiring multiple lasers or multiple gases.

The measurement of ILS requires an isolated spectral feature, either an emission line or absorption line. The ideal separation between spectral features is 10 times the width of the ILS or more. The potential candidates are lasers and gas cell absorption from various gases. Accurate ILS characterization requires a source assembly that fills both the field of view and the pupil of the sensor. There needs to be at least one spectral signature per band.

The measurement of unapodized spectral resolution, the resolution after the self-apodization effects such as the off axis location and FOV size are removed from the spectrum, requires a spectral signature with two closely spaced lines, at or near the resolution requirement. For this requirement only one spectral signature per band is needed. Similar to the ILS characterization, the resolution measurement requires a broadband source to illuminate the various gases, one per band, which will be chosen. Another approach to measuring the unapodized spectral resolution is to "deconvolve" the self-apodized ILS from the measured spectra and determine the width of the residual ILS, which should then equal the ideal sinc function obtained from the MPD.

Reviewing the brief concept descriptions above, the following test requirements are present:

1. Optical system that fills the pupil and field of view of the sensor
2. Broad band IR source or blackbody
3. Horizontal and Vertical Slit targets for linear scans
4. Spot target for raster scans
5. Input radiance with well-known spectral line(s), one per band
6. Spectral signature with isolated spectral lines, two per band
7. Spectral signature with closely spaced lines, one per band

4.3 Further Concept Development

Even though the concept of slit and spot scans appears to be the concept of choice, there are still different approaches to accomplishing the measurements that need to be evaluated and one method selected. The first such evaluation is the field of view of the optical system or collimator. Will the collimator have a one-degree field and be translated or will the collimator have a 3.3 degree field with translation of a target within the collimator? The collimator has to be at least a one-degree field of view to fill the field of an individual FOV in the CrIS. To be able to fill all nine FOVs at one time requires a collimator with a 3.3 by 3.3 degree field of view. Since the one-degree field already puts the collimator in the category of a three-mirror anastigmat (TMA), the question becomes whether a TMA will have sufficient image quality and pointing accuracy at the 3.3 by 3.3 degree field. A feasibility study or design study was then performed by LWO for the TMA at 3.5 degrees. The result of the study said that the TMA could be made to satisfy the field of view and pointing accuracy requirements. This was much preferred over the alternative of designing a large five or six degrees of freedom positioning system for moving the one degree collimator to each of the nine FOV locations with an accuracy of 20 microradians. In addition fitting such a large translation system in the vacuum chamber would be a real challenge.

Another concept trade that needs to be made is the one between lasers and gases for the spectral signatures during ILS and spectral calibration. Looking at the requirement for ILS, a single frequency laser would be ideal for ILS. It is the only spectral line present and thus well isolated from any other interferences. If there were one or more lasers in each spectral band then lasers would be the choice for ILS. In the end however, the only lasers that are available that are narrow line single frequency operation lasers are the CO2 and a quantum cascade at 1088 cm^{-1}. This means that gas absorption needs to provide the spectral signatures for ILS and spectral calibration in at least the MWIR and the SWIR bands. For comparison purposes it will be most instructive to have both gases and lasers available in the LWIR spectral band.

Carrying the concept development to the next lower level, the test developer would begin to address the selection of gases for the ILS and spectral calibration tests. For the gas cell ILS measurement the gas(es) for each band needs to have reasonably well isolated absorption lines. Searching the databases available (HITRAN, NIST, IUPAC and PNNL) the following gases were found with lines present and useable within the CrIS spectral bands: NH3, CH4, C2H2, CO2, CO, HBr, DBr, and DCl. At this point the concept development may require more detailed analysis of gas absorption to determine the best choice of gases. The concept developer knows that there are gas absorption spectra that are available for use and are definitely a part of the test concept.

4.4 Test Error Analysis

As stated earlier the allocation for measurement uncertainties need to be decomposed into the test error sources. Based on the test concept for ILS described in section 4.2 and the allocated measurement uncertainty of 0.5%, the Ground Characterization Uncertainty for ILS has contributions shown in figure 5. Some of the factors that determine the ILS Shape Uncertainty include the uncertainties in the line width of chosen line, field of view size, location relative to the interferometer optical axis, MPD, and tilt between the arms of the interferometer. Also variations in the velocity and modulation as a function of OPD are factors that contribute to errors in the FWHM. Data processing techniques and algorithms will also impact the error in the measurement. Since a model is needed for the "deconvolution" of ILS from the measured spectrum the errors in the model will introduce errors in the results for ILS. Even the interpolation performed to find the FWHM will add uncertainty to the measurement. All of these are also impacted by the noise in the measured data, which is determined by the measurement SNR and the number of spectra coadded.

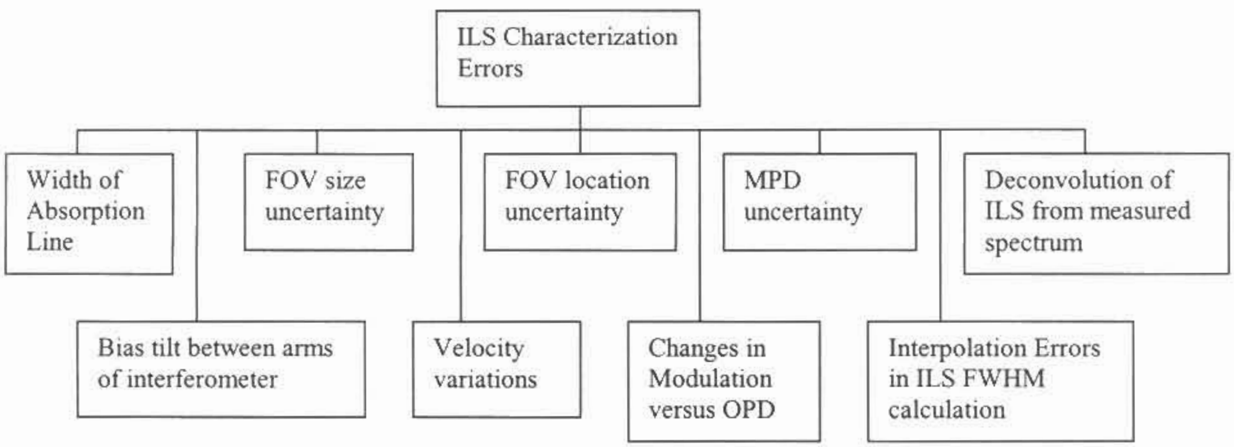

Figure 5 ILS Characterization Error Allocation Tree

5. TEST COLLIMATOR

The discussions in the preceding sections outline the basic requirements for a collimator system that will be needed to perform the spatial and spectral characterizations. The collimator is an excellent example of the flowdown of the requirements from the system level to the test equipment. This collimator has been developed under ITT capital funding as a general purpose wide field of view optical system with the first application being CrIS.

5.1 Collimator Requirements

For both spatial and spectral characterizations the collimator needs to fill the field and the pupil of the CrIS. Therefore, the optical system needs to have a field of at least 3.3 degrees by 3.3 degrees and a pupil size greater than 80 mm at the entrance pupil of the CrIS. The spectral bands of CrIS extend from 650 cm^{-1} to 2550 cm^{-1} (3.9 to 15.4 micrometers).

Thus the system transmission needs to be high throughout this region of the infrared spectrum. For mapping out the FOV response there need to be targets and the ability to move the targets in the focal plane of the collimator. The motion of the targets needs to allow for horizontal and vertical scans. The required targets are a slit that can be rotated or separate horizontal and vertical slits, a spot and an open position. Since the collimator system is also for use in the vacuum chamber, separate targets are needed for the horizontal and vertical slits. The pointing accuracy of the collimator needs to be better than the 40 microradians required for mapping uncertainty. The boresight measurement requires a method for assessing the alignment of the collimator to the sensor. Therefore, there is a requirement for a reticule target that will be used with a visible source to measure the alignment of the collimator FOV to a reference on the CrIS sensor.
For spectral measurements the system needs to have at least the gas cell and possibly the laser and integrating sphere in the source path. Using these requirements as the starting point, the key collimator requirements have been derived and are listed in Table V, shown later in this section.

One derived requirement for the collimator is the filter wheel. As with any spectral type sensor it may be useful to band limit the input for certain test conditions, such as during the gas cell measurements. The filter wheel allows for two narrow band filters for each spectral band of CrIS to be put into the wheel. The aperture block, an open aperture and potentially a spectral balance filter, which would be used, if needed, to balance the input so that all three spectral bands can be measured simultaneously, occupy the other slots on the wheel.

5.2 Collimator Block Diagram

Figure 6 shows a block diagram schematic of the collimator system. Since the collimator will be primarily used for infrared characterizations, there needs to be a source of infrared radiance and that is the High Temperature Blackbody (HTBB). The HTBB source has a controller for controlling its temperature. In addition there is a circulator that is used to help cool the HTBB when in the chamber. The gas cell is a 100 mm aperture with 100 mm path length gas cell having ZnSe windows that are slightly wedged and AR coated. The gas cell has the capability to be heated and thus also has a temperature controller. The gas cell also has a cooling line associated with it to help cool it as well. The filter wheel is a 9 position wheel accepting 80 mm diameter filters with as much as an 8 mm thickness. The position of the filter wheel is controlled using a stepper motor and controller. Note that the filter wheel will only rotate +/-180 degrees, as the temperature of the aperture block is monitored via PRTs and thus has wires attached. The target wheel has 5 target positions. Each target is aligned to the axes of the collimator to 0.01 degrees. There is a rotary stage that allows for the selection of the target. There are two linear stages that will translate the target wheel in steps as fine as 0.1 micrometer. These stages are controlled and have encoders on each axis. Each of the three primary targets, slits and spot, are temperature monitored as well. In addition to the two cooling lines mentioned above there is also a set of tubing for introducing the gas into the gas cell remotely. Because this system will be used in the vacuum chamber, the gas cell needs to be filled and evacuated from outside the chamber. In addition there is a pressure gauge outside the chamber as well to monitor the pressure in the gas line. Then there is the collimator optical system that collects the IR radiance passing through the target and collimates the radiance and images the entrance pupil, the HTBB aperture, at the sensor entrance pupil.

5.3 Collimator Optical Design

The design of the collimator optical system is a three-mirror anastigmat (TMA) design. This configuration is necessary to meet the wide field of regard requirement. It is an all-reflective design with the exception of the gas cell and any filters that are inserted in the optical path. Each of the mirrors in the optical design is a general asphere and thus will need to be single point diamond turned. Figure 7 shows a layout of the optical system with the gas cell and filter included in the optical path. The optical prescription for the three major mirrors is given Tables III and IV.

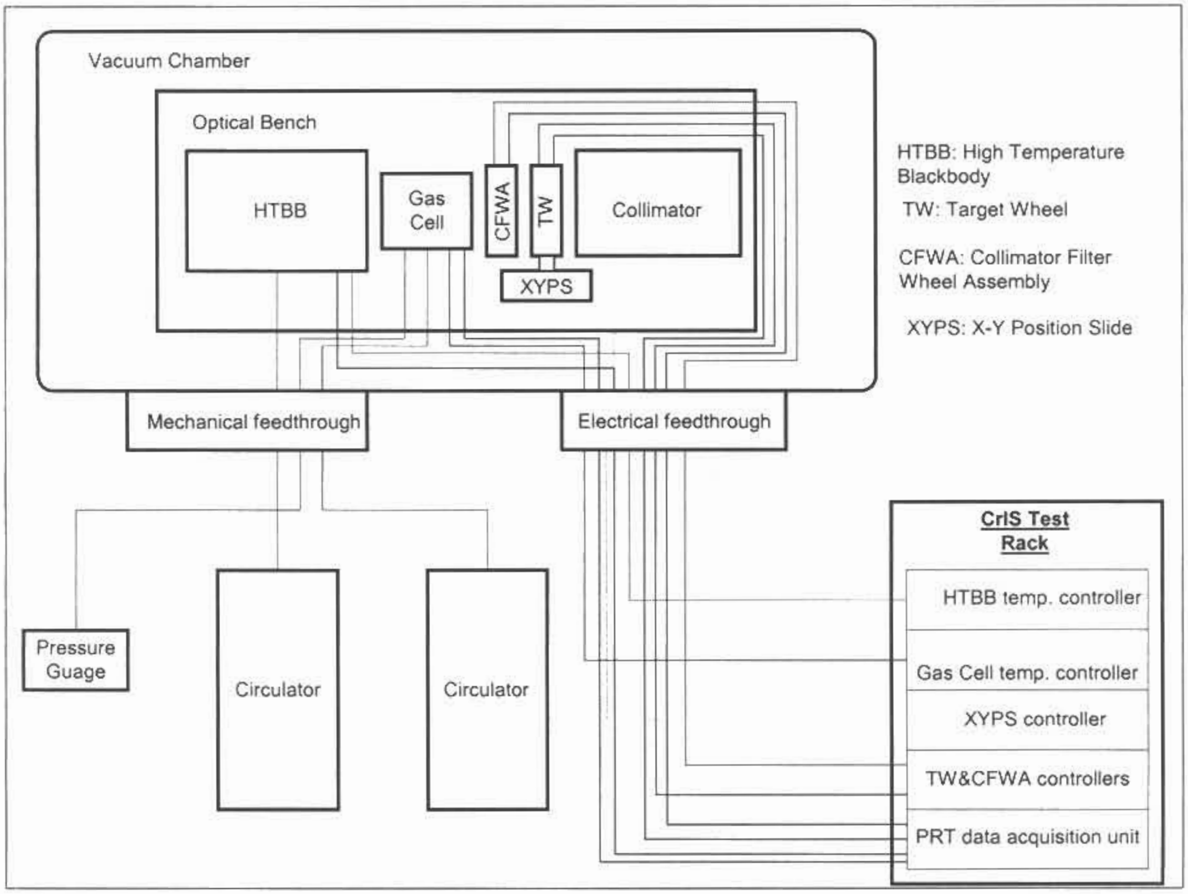

Figure 6 Collimator Block Diagram, Vacuum Chamber Configuration

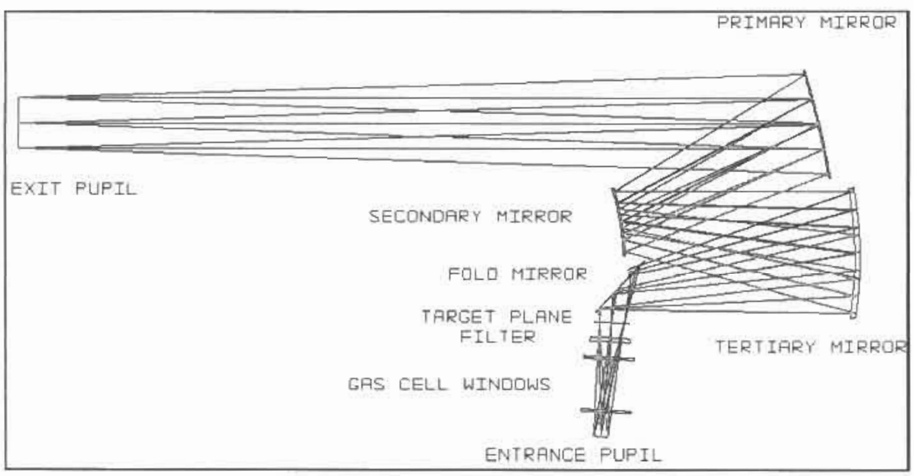

Figure 7 Collimator Optical Layout

Table III Collimator Optical Prescription

1	Aperture Stop	infinity	1638.7098
2	Y-decenter	-372.9635	0.0000
3	Y-tilt	6.7381-dg	0.0000
4	Aspheric – Primary	-1603.4200	-422.7410
5	Y-decenter	9.1181	0.0000
6	Aspheric - Secondary	-546.5609	0.0000
7	Y-decenter	-9.1181	465.9210
8	Aspheric – Tertiary	-805.1966	-557.9522
9	Image	infinity	-229.8905
10	Exit Pupil	infinity	

Table IV Aspheric Surface Table of Constants

	Conic Constants	A4	A6	A8	A10
Primary	-1.506989e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
Secondary	5.333790e+00	4.161034e-09	3.640361e-14	1.496206e-18	-1.200273e-23
Tertiary	2.155080e-01	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00

The optical system performance analysis shows that this design meets the requirements in most cases and exceeds the requirements in many areas. The wavefront errors are a key parameter for evaluating the design. Figure 8 shows the predicted on axis wavefront error of 0.32 micrometers peak to valley and the predicted off axis wavefront error of 0.48 micrometers peak to valley.

The predicted wavefront slope errors are shown in figure 9. Here the circle represents the requirement for slope error, which is 16 micrometers radius for the 800 m focal length system. The errors are within the requirement.

The analysis predictions of performance shown in Table V verify that the design will meet the system requirements. The table shows the specified requirement value and the predicted performance value.

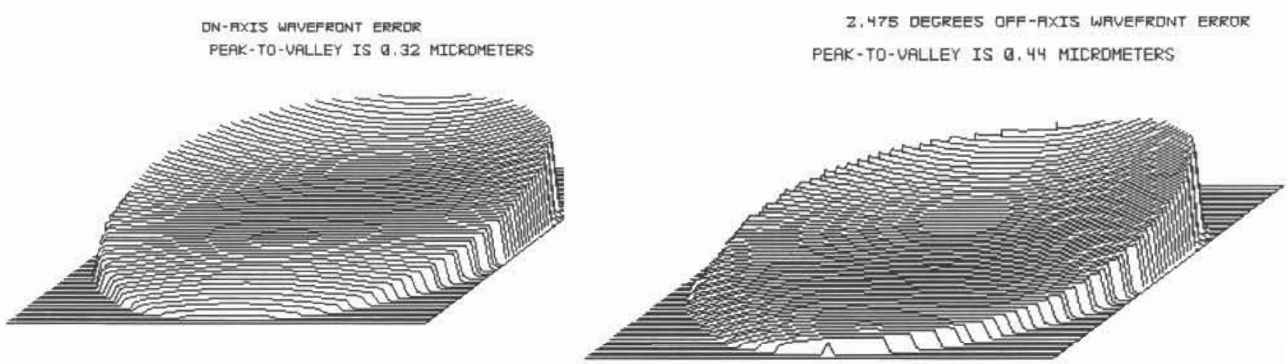

Figure 8 Collimator Predicted Wavefront Errors

One of the important requirements for the collimator is the pointing accuracy. For the distortion of 0.275% the pointing errors will be greater than the 30 microradians required. Therefore the pointing accuracy will be calibrated to the 30 (with a goal of 20) microradian level by using a theodolite to measure the angular output of the collimator as a function of the target position. Thermal and structural analyses have shown that the system will be very stable over the limited temperature range of operation 10 to 30 C and input vibration levels of TBD. Thus the calibration of the pointing is expected to be good for the life of the collimator.

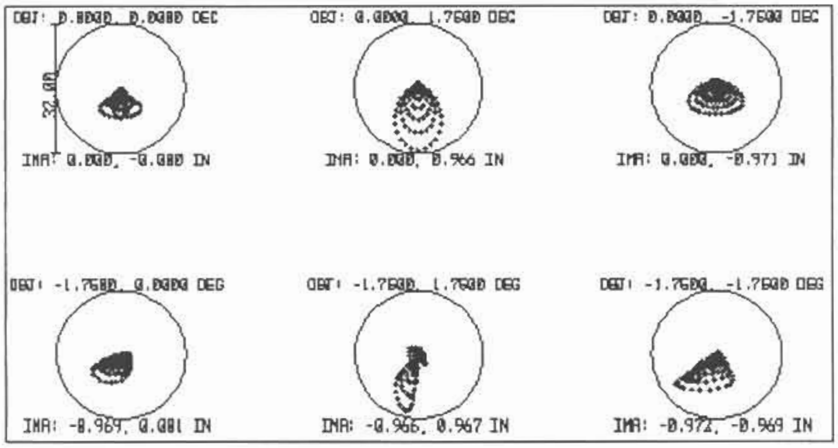

Figure 9 Spot Diagrams Showing Slope Error Predicted Performance

Table V Collimator Requirements and Predicted Performance

Requirement	Specified Value	Predicted Value	Units
EFL	>750	800	mm
EFL stability	0.10%	<0.10%	
FOV	3.5 x 3.5	3.5 x 3.5	degrees
Replaceable entrance aperture	Required	Yes	
Exit pupil diameter	100 to 200	101.6	mm
Exit pupil location	at UUT	at UUT	
Allow limiting exit pupil to 80 mm	Required	Yes	
Entrance pupil at blackbody	Required	Yes	
Spectral Transmittance 3.4-15.4 mm, Gas Cell	>54%	>54%	
Spectral Transmittance 4-13 mm, Gas Cell	>80%	>80%	
Spectral Transmittance 3.4-15.4 mm, Collimator Optics	>90%	>90%	
Spectral Transmittance 0.5-0.8 mm	>25%	>25%	
Spectral Transmittance 3.4-15.4 mm, HTBB window	Maximized	Maximized	
Spectral Transmittance 4-13 mm, HTBB window	>90%	>90%	
Wavefront error, center	1.0	0.32	μm
Wavefront error, 2.475 degrees off axis	2.0	0.44	μm
Slope of wavefront error < 0.5 um per 25 mm	2.0E-05	<1.2E-05	radians
Pointing accuracy, distortion	<1.0%	<0.28%	
Line of sight measurement	+/-30	+/-30	μr
Line of sight stability, bench level	<5	<0.5	μr rms
Line of sight stability, bench and chamber level	<25	<5	μr rms
Line of sight pointing, bench and chamber level	<10	<10	μr rms
Vignetting, over field of view	none	none	
Stray energy, as a percent of maximum signal	<1 %	<1 %	
Collimator illumination uniformity, exit pupil	<2%	<2%	
Collimator illumination uniformity, 1 degree FOV at target	<2%	<2%	
Reticule target resolution	<10 μR	comply	
Polarization	<3%	1.30%	
Collimator target extended field	>4x4	> 4x4	degrees

5.4 Mechanical design of the collimator

Based upon the need for SPDT optical elements, structural and thermal integrity and ease of manufacture, the material selected for the optical bench and optical components is aluminum. The frame or housing for the optical bench will also be aluminum. This makes for a stable and rugged design that is easily manufactured. Figure 10 shows the mechanical model for the Collimator Assembly. The primary mirror is approximately 11 inches square and three inches thick so has been light-weighted to keep the overall weight of the system down to 325 pounds. The secondary mirror is supported by the tower as shown in the figure below the primary mirror. The tertiary mirror is located inside the secondary support tower directly below the primary. The tertiary mirror is approximately 12 inches square but is only 1.5 inches thick. Three mounting pads, which are lapped coplanar, are used for the mounting of each of the mirrors. Locating pins and liquid pinning of the mechanical and optical components ensures that the alignment will be very stable. The structural analysis for the system shows that the aluminum bench provides the structural stiffness needed to keep the fundamental frequency above 60 Hz.

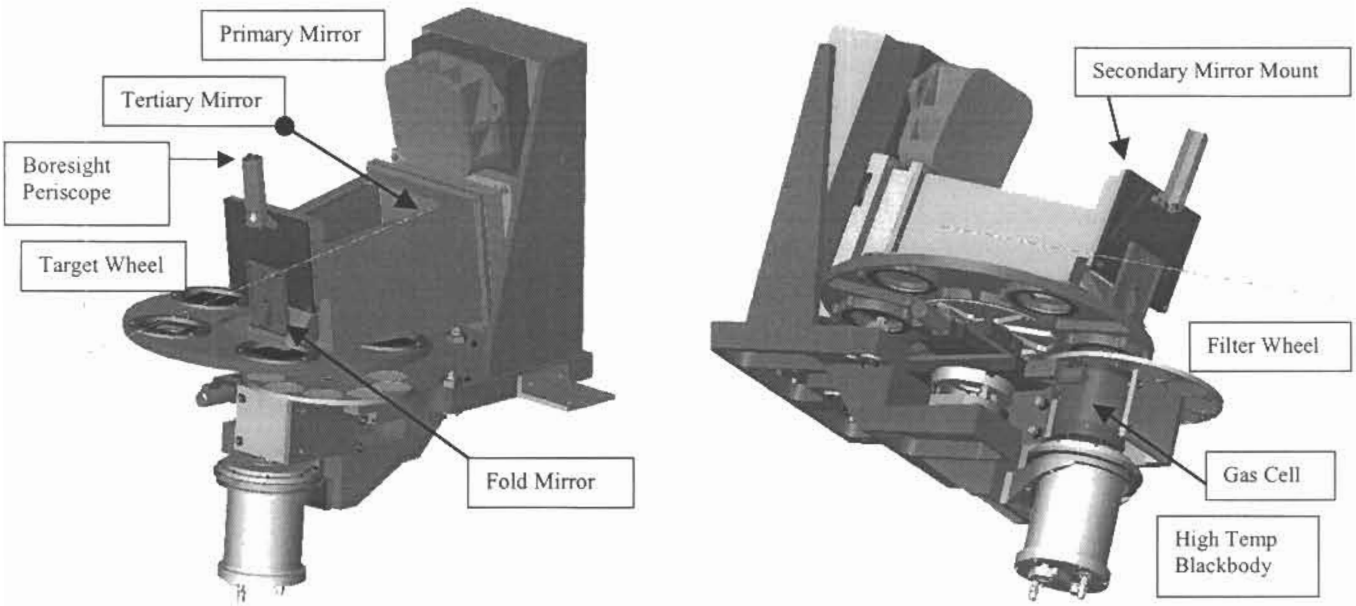

Figure 10 Collimator System Opto-Mechanical Assembly

5.5 Initial Wavefront Measurements

Following the collimator optical alignment of the TMA, a series of wavefront measurements were made. These wavefront measurements include data taken at 25 field positions within the collimator field of view. The on-axis wavefront error occurs at row 3 and column 3 and as shown in Table VI is 0.62 micrometers, where the requirement is 1.0 micrometer peak-to-valley (P-V). The worst-case off-axis P-V wavefront error is 0.9 micrometers, when the requirement is 2.0 micrometers P-V. The performance of the collimator optics is exceeding the requirements for wavefront error.

Table VI Peak to Valley Wavefront Error for 25 Field Positions

	P-V	Column				
		1	2	3	4	5
Row	1	0.859	0.783	0.738	0.712	0.836
	2	0.723	0.722	0.588	0.568	0.802
	3	0.704	0.705	0.627	0.803	0.743
	4	0.857	0.737	0.65	0.727	0.884
	5	0.796	0.851	0.787	0.905	0.902

6. MODELS AND SIMULATIONS

One of the key tools leading to increased understanding of an instrument's performance is an instrument model or a simulation. The simulation or model predicts the performance of the instrument based upon the mathematical equations that are used. The agreement between model and measurement depends upon the degree to which the assumptions made in the model match to the real measurement situation. In addition the agreement depends upon whether the correct parameters have been included and modeled properly. These models are also very useful to the test development. Models predict the response of the sensor or predict the behavior of the input to the sensor and are critical to the understanding of the output of the test.

6.1 ILS Model

An example where models have been used is the ILS and spectral calibration test. In the case of the ILS, an ILS model has been developed to predict the effects of the off-axis fields of view of the CrIS sensor on the width and shape of the ILS, as well as the spectral shift introduced by the off axis fields. This model is based upon the ILS computation method given by J. Genest and P. Tremblay. [Ref. 7] Use of this model has helped us better understand the limits over which the ILS can be assumed to be constant. In the case of CrIS this spectral width is very narrow, only a few wavenumbers. Figure 11 shows the predicted ILS for the corner FOV at 650 cm^{-1} and figure 12 shows the predicted ILS at 1095 cm^{-1}. The FWHM prediction at 650 cm^{-1} is 0.78 cm^{-1} whereas the prediction at 1095 cm^{-1} is 0.85 cm^{-1}. Nearly a 10% change in ILS FWHM across the longwave band. Clearly the prediction of such a large change in ILS FWHM leads to the conclusion that a "deconvolution" using a single ILS over the longwave band will not be sufficiently accurate. (In fact the extraction of the ILS from the measured spectrum becomes a matrix inversion problem.) Also from the model the spectral shift is also observed. For 1095 cm^{-1} the shift is 0.439 cm^{-1}.

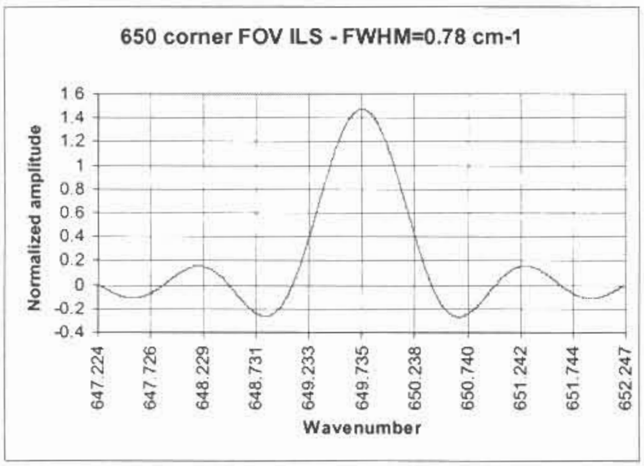

Figure 11 ILS for LWIR Corner FOV at 650 cm^{-1}

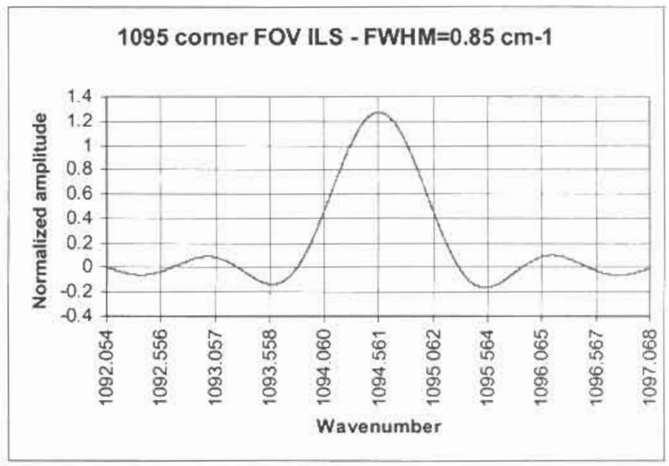

Figure 12 ILS for LWIR Corner FOV at 1095 cm^{-1}

6.2 Gas Absorption Model

Another model or simulation tool used to help visualize and quantify the spectral tests is a gas absorption model. HITran PC using the HiTran database has been used to model a number of gases for use in the gas cell. The theoretical spectra help us to select the gases and pressures and temperatures that will provide a reasonable absorption that is not saturated or broadened. In addition the resolution of the sensor can be added to provide a realistic spectral output of the sensor. Figure 13 shows the transmission spectrum of carbon monoxide at 10 TBD Torr at 296 K in a 10 cm gas cell. Note in this figure that the scale is from 96% to 100%. The peaks of the absorption lines at the CrIS resolution will only be a few percent.

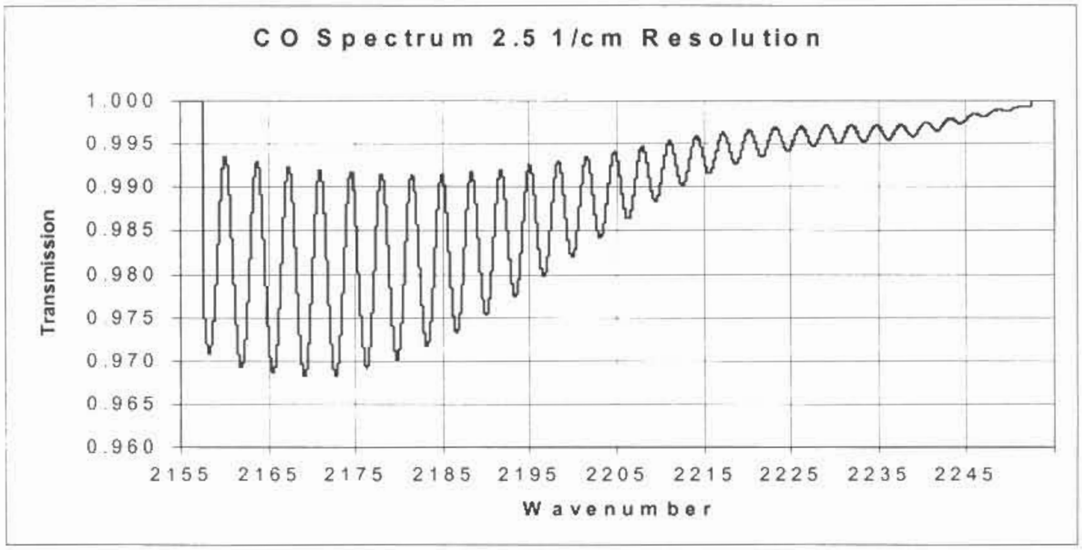

Figure 13 Simulation of Carbon Monoxide Gas Transmission Spectrum

6.3 Edge Response Model

Another example of a simulation is the generation of edge response curves. The software analysis tools, such as Zemax and Code V can be used to simulate the response of an edge as it is scanned across the field of view. Figure 14 shows such a simulation for the worst-case longwave field of view. From the edge response curve the encircled energy can be predicted as well as other field of view parameters. The figure shows that at the longwave edge of the LWIR band the encircled energy is slightly below the 95% requirement. Also the edge response shows that the tails of two FOVs will overlap slightly. These simulations are extremely useful for corroborating the test results.

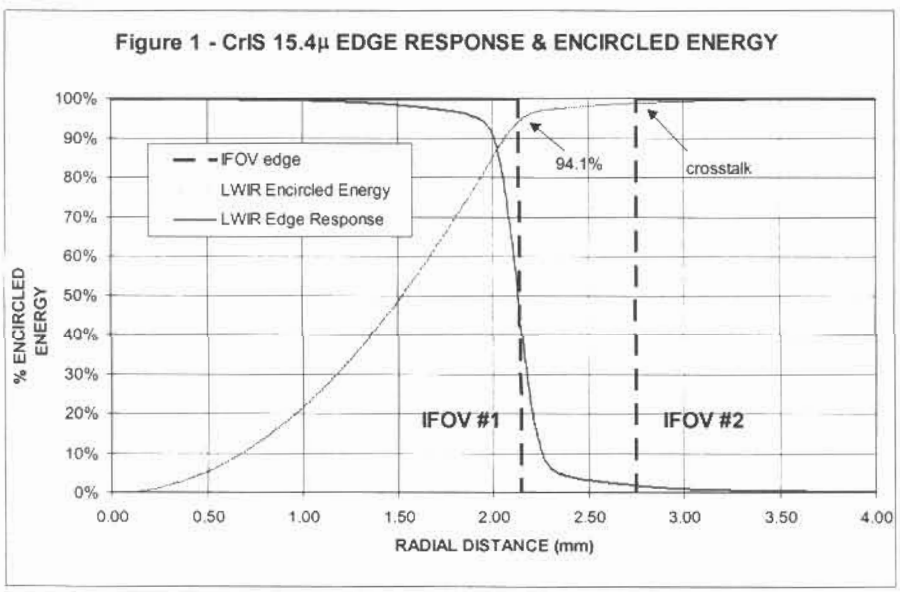

Figure 14 CrIS 650 cm^{-1} Edge Response and Encircled Energy

7. SUMMARY AND CONCLUSIONS

The test development for the spatial and spectral characterization of the CrIS sensor involves the understanding of the sensor level and module level requirements being verified by test. The allocated requirements need to be understood so that further allocations to the test process and test equipment will be done correctly. The collimator requirements development was shown as an example of this process. The collimator is the key enabling hardware for the spatial and spectral measurements. Finally models and simulations are a key part of the verification process. Models such as those for gas absorption, ILS and edge response are a few examples.

8. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the guidance and support of the NPOESS Integrated Program Office (IPO) which directs the CrIS program, its Operational Algorithm Team (OAT) which supports algorithm development, and the staff of MIT Lincoln Laboratory who provided interferometer technical support to the IPO. In addition, a talented and dedicated CrIS team at ITT Industries and other team member locations contributed to the development of the CrIS system design.

The authors acknowledge the contributions of the many people who have worked and continue to work on the test development in the areas of spatial and spectral measurements. The authors acknowledge Bill Morgan, Don Small, Dan Barber, Tony Holloway, Ed Howes and the rest of the staff at LightWorks Optics for their work to help design, development and build of the collimator; Martin Chamberland and Louis Belhumeur of Telops and Norm Macoy and Joseph Lawrence of ITT for their work to develop the new ILS model as well as overall development of the spectral tests; Brad Cameron, Rich Kohrman, Brian Tiffany and Glen White of ITT for their contribution to the development of the collimator specifications and design; Dave Wickholm and Jay Overbeck for their contributions to the spatial test development.

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